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Techno-economic analysis of enhanced dry cooling for CSP

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Abstract

Evaporation cooling systems are currently deployed in the majority of operating Concentrating Solar Power (CSP) plants. However, the fundamental drawback of this approach is that large quantities of water are used in the cooling tower, so that this solution will be not applicable for a large-scale CSP development in arid regions. In fact, in most of the sites suitable for CSP applications, ambient temperatures are typically high and water is scarcely available, or the cost of transporting water to these sites is prohibitive. For this reason, at these sites dry cooling will be the only viable option. This paper analyses the impact of dry cooling systems on technical and economic plant performances, considering several condenser layouts, different operation strategies and economic boundary conditions. In particular, the capacity and the operation of the thermal energy storage can be optimized in order to maximize power production, e.g. by preferential plant commitment at night hours. The analysis is carried out for three selected locations with real meteorological data by means of annual simulations with hourly time steps.

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Keywords: Dry cooling; optimized plant commitment; temperature impact on power block efficiency

1. Introduction and background

A key step of the power generation in Rankine processes is the condensation of the exhaust steam. The steam has to be condensed and returned to the steam generator. The lower the condensation temperature, the higher the conversion efficiency of the power block.

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Nomenclature

a	[Mio. €/y]	annuity
A	[m²]	heat transfer surface area
ACC		air cooled condenser
C_a	[Mio. €/y]	annual capital cost
$C_{O\&M}$	[Mio. €/y]	annual operation and maintenance cost
$C_{insurance}$	[Mio. €/y]	annual insurance cost
CAPEX	[Mio. €]	capital expenditures
CSP		concentrating solar power
DLR		German aerospace center
DNI	[W/m²] or [kWh/m²/y]	direct normal irradiance
EPC		engineering, procurement and construction
EPRI		electric power research institute
EY	[GWh/a]	annual net electricity yield
ITD	[K]	initial temperature difference
LEC	[€cent/kWh_{el}]	levelized electricity cost
LMTD	[K]	logarithmic mean temperature difference
NREL		national renewable energy laboratory
OPEX	[Mio. €/y]	operational expenditures
P_{el_net}	[MW]	net electricity generation
PB		power block
PCM		phase change material
PPA		power purchase agreement
Q_{cond}	[MW_{th}]	heat rejected by the condenser
REMix		renewable energy mix (energy systems optimization model)
SF		solar field
SoC	[-]	state of charge (of the thermal energy storage)
T_{cond}	[°C]	steam condenser temperature
T_{DB}	[°C]	dry-bulb temperature
TES		thermal energy storage
TTD	[K]	terminal temperature difference
U	[W/m²/K]	heat transfer coefficient
ζ	[%]	plant availability

In addition, the choice of the cooling system has a large impact on capital expenditures (CAPEX), operational expenditures (OPEX), auxiliary loads and water requirements. Different cooling configurations are in principle possible:

- **Once-through:** in this system the required cooling water is withdrawn from a water reservoir (e.g. river, lake or sea). The cooling water passes through the tube-side of a heat exchanger and takes the condensation heat of the steam turbine exhaust. Downstream the condenser, the heated cooling water is returned to the water reservoir. This cooling option is characterized by simple layout, high efficiency, low capital cost and relatively low auxiliary power requirements (see Table 1). For these reasons once-through cooling historically was the preferred cooling option at sites with large water availability. However, in the last years its use has been limited or even prohibited due to environmental issues.
- **Recirculating/**evaporative: this condensation process relies on the wet bulb temperature instead of on the dry bulb temperature, as it is the case in dry cooling. This means that evaporative cooling systems are capable to achieve in general lower steam condensation temperature than dry cooling systems [1]. Similar to once-through systems, in recirculating or evaporative cooling systems the steam is condensed in water-cooled heat exchangers.

However, in this case the heated cooling water is not directly returned to the environment. Rather, it is recirculated between the turbine heat exchanger and a cooling tower or the water is at least cooled down before lead back to the water reservoir. In the tower, the heated cooling water is sprayed by nozzles onto a tube bundle [2]. The remaining cooled water is collected in a basin located at the bottom of the tower and recirculated again towards the steam condenser. The evaporation share typically amounts to approx. 2 % of the recirculating water flow. In comparison to once-through systems, the total water consumption (incl. water withdrawal) can be reduced up to 90 % [3], [4]. Main disadvantages of recirculating cooling are lower efficiency when directly compared with once-through systems, higher CAPEX, higher auxiliary load and complex layout (Table 1). In addition, chemical pre-treatment of makeup water and blowdown flow is required.

- **Dry cooling**: this cooling method is governed by the dry bulb air temperature. The heat rejection performance of the dry-cooling system under varying ambient weather conditions and the thermodynamic performance characteristics of the turbine are closely interrelated [5]. Dry cooling systems can be realized with direct or indirect layout. In direct systems, exhaust steam from the turbine is transported to an air-cooled condenser (ACC). By the 90s, a series of large-scale dry-cooled systems were installed mainly in coal fired plants in the United States and in South Africa. An alternative approach to dry cooling is represented by the indirect layout. Particularly interesting are the so-called Heller systems. Similar to other indirect cooling configurations, these systems are equipped with a separate condenser. The main difference with other indirect cooling designs is the barometric condenser, where the steam is condensed directly by a spray of cooling water. Thereby it is possible to achieve very low (0.5 K) terminal temperature differences (TTD) compared with conventional surface condensers (3 - 4 K) [6].

A summary of the features of different cooling technologies is presented in Table 1.

Table 1. Overview of cooling system characteristics [4], [7], [8]

	Once-Through	**Recirculating Cooling**	**Dry Cooling**
Layout	simple	complex	complex
Impingement/ Entrainment	yes	yes	no
Thermal Plume	no	yes	no
Water withdrawal	very high	low	no
Water consumption for cooling purpose	yes (indirect)	yes	no
Reference Temperature	water reservoir	wet bulb	dry bulb
Power block efficiency	high	medium	low
Planning Approval Process	normal	normal	quick
CAPEX	low	medium	high
OPEX	low	high	high
Heat Exchanger Lifetime	30 years	10 years	30 years

From the information provided above, it becomes clear that the site selection of a steam power plant plays a key role in the selection of the cooling technology. On the other side, there are often specific reasons to locate a plant at a particular site. This is the case of plants located near to load centers, transmission corridors, or in the proximity to low-cost fuel sources, but where water availability is very limited. This was the case for a number of coal-fired plants in South Africa, which were located near to coal extraction mines. The same applies to Concentrating Solar

Power (CSP) plants. In fact, the highest potentials of direct normal irradiance (DNI) typically are located in regions where water is scarce, absent, or the water transportation cost to these sites would be prohibitive. Even if evaporation cooling systems are currently deployed in the majority of operating CSP plants in Spain, this solution will be not applicable for a large-scale CSP development in arid regions. For this reason, at these sites dry cooling will be the only viable option. Driven by increasing interest of industry in dry cooling, a number of reports dealing with this technology have appeared [5], [9], [10]. Several approaches for the enhancement of dry cooling systems have been proposed for conventional plants as well as specifically for CSP. Among them count hybrid dry-wet cooling [8], [11], deluge cooling [10], [3], [8], ACC design optimization and optimized plant dispatch [3], [12].

2. Methodology

This paper analyses the impact of dry cooling on CSP plants. Technical and economic plant performances are presented for selected cases. The CSP model is not presented as it is not of direct interest to this paper. However, the simulated CSP plants are typical parabolic trough plants with a synthetic Heat Transfer Fluid (HTF) with 2-tank indirect molten salt thermal energy storage (TES). The used temperature and DNI data have been gathered from Meteonorm. The first part of the paper deals with the description of the implemented dry cooling model. In particular, characteristic lines for the performance of dry-cooled CSP steam turbines (temperature-dependent efficiency and cooling fans auxiliary load) have been provided by the company enolcon. In addition, a cost model has been developed. After the dry cooling model has been set, several ACC condenser layouts for CSP plants are investigated by means of an Excel-based tool. This tool has been implemented for the quick assessment of different CSP plant configurations and for parametric studies. Within this work, the model has been adapted in order to investigate the impact of key plant parameters such as solar multiple and specific solar field investment cost on optimal ACC design. The analysis reported in the further part of the paper shows that the operation of the thermal energy storage can be optimized in order to maximize power production, e.g. by preferential plant commitment at night hours, taking advantage of the higher efficiency of the power block. Due to the complexity of this task, the analysis is carried out with the optimizing tool REMix. REMix is a DLR in-house cost-minimizing model designed for the analysis of electricity supply systems with a high share of renewable energies. A comprehensive database containing techno-economic parameters of a broad range of CSP as well as other renewable and conventional technologies is included in the model. Within this paper, the REMix CSP model is used in order to investigate the performance of the analysed dry-cooled CSP plants. The model is capable of optimizing the plant configuration (solar field size, thermal storage capacity, dry-cooling condenser layout) as well as the plant dispatch during each hour of the simulated year. The analysis is carried out for three selected locations in Jordan and for different economic boundary conditions (time-constant feed-in price and demand-proportional feed-in price).

3. Dry cooling model

3.1. Technical model

The ambient dry-bulb temperature (T_{DB}) has a major influence on the efficiency of the dry cooling unit. For a given layout, the achievable steam condensation temperature (T_{cond}) can be calculated as:

$$T_{cond} = T_{DB} + ITD \tag{1}$$

Typical ITD values of conventional plants constructed in the last years vary between 20 and 40 K [13]. Assuming that for a given plant the heat which has to be rejected (Q_{cond}) is constant, the choice of the ITD influences power block efficiency as well as investment cost:

$$Q_{cond} = A \cdot U \cdot LMTD = A \cdot U \cdot \frac{ITD - TTD}{\ln\left(\frac{ITD}{TTD}\right)} \tag{2}$$

In Eq. 2 A is the heat transfer surface area of the condenser [m²], U the heat transfer coefficient [W/m²/K] and LMTD the logarithmic mean temperature difference [K]. The choice of a low ITD will increase the power block efficiency on the one hand, but on the other hand will increase the investment cost of the condenser. Conversely, a high ITD will correspond to lower investment cost but also lower efficiency. As it will be shown in the results, the optimal ITD for a CSP plant is a function of several parameters such as solar field layout and specific investment cost of different plant components.

3.2. Design point specifications

Other than recirculating cooling systems, which are often designed for the highest wet-bulb temperature of the year (99 % occurrence) [4], the design point temperature of dry cooling units typically is much lower than the maximal dry-bulb temperature. These choices are mainly due to techno-economic considerations. As a main consequence of this design, dry cooling suffers from the inability to maintain design plant output during the hottest hours of the year. A plant can experience up to 20 % capacity reduction during these periods, which moreover are often characterized by peak demand [10]. In order to enable a direct comparison of the influence of the cooling system at different sites other boundaries like site elevation, wind effects and other environmental conditions are kept constant in the following study. The design point dry-bulb temperature of the cooling system has been defined as the temperature which is undershot in the 80 % of the time in a typical meteorological year. If the CSP plant is in operation, during the remaining 20 % of the time the turbine will run with reduced efficiency. However, the design of an ACC is depending on different boundaries like tariff structure of a power purchase agreement (PPA), power price, financing frame conditions, purchase price, etc. [14]. These boundaries have to be considered in a detailed case study at every specific site. Therefore the used design claims not the right to be in every case the economical optimal solution. Nevertheless other ITD values and power block properties can be alternatively considered and thereby the introduced approach can support (project developers and EPC providers) during the engineering phase in order to design the most economic feasible plant adapted to the specific boundaries. A simplified cost model for the consideration of different dry cooling design temperatures is presented in the next section.

3.3. Cost model

A cost model for the whole CSP plant has been developed in order to take into account the impact of the different dry-cooling designs on the levelized electricity cost (LEC). The same cost model has been used for the analysis in the simplified Excel-tool as well as in REMix. An overview on the chosen assumptions is given in Table 2. The investment cost of the cooling system has been calculated separately, as it depends on the ITD of the dry cooling heat exchanger. Cost estimation for different dry cooling designs has been provided by the company enolcon [15]. The assessment has been performed assuming a CSP power block gross efficiency of 37.8 % at design point. It should be pointed out that the specific investment values assumed in the current study result in lower CAPEX than in previous works [14]. The cost assumptions taken within this study -in combination with the design point specification exposed above- are likely to lead to a different optimal ITD values than in [14].

Table 2. overview on economic and financial assumptions for the parabolic trough CSP plant (monetary values in $€_{2013}$)

Economic Assumptions	Value	Unit
Depreciation time	15	y
Weighted average cost of capital (WACC)	8.10 %	%
Costs - SF	300/200/100	€/m²
Costs - TES	45	$€/kWh_{th}$
Costs - PB (w/o cooling)	733	€/kW
Costs - cooling system	ITD-dependent	€/kW
Costs - backup	42	$€/kW_{th}$
O&M	2.0 %	% CAPEX/y
Insurance rate	0.5 %	% CAPEX/y
Owner´s cost	730	€/kW

The following correlation has been used:

$$spec.CAPEX_{DRY\_COOL} = 0.7437 \cdot ITD^2 - 48.721 \cdot \mathrm{ITD} + 1017.1 \quad (3)$$

The specific CAPEX is expressed in [$€_{2013}/kW_{el}$], while the ITD is in [K]. The cost of the dry cooling is assumed to include finned tube heat exchanger unit, fans and motor, support structure and steam exhaust piping. The LEC is calculated as the sum of annual capital and operation cost divided by the net annual power generation:

$$LEC = \frac{C_a}{EY \cdot \zeta} = \frac{a + C_{O\&M} + C_{insurance}}{EY \cdot \zeta} \quad (4)$$

where C_a is the sum of the annual plant cost, which consists of annuity a, operation and maintenance cost $C_{O\&M}$ as well as insurance cost $C_{insurance}$. All costs are expressed in [Mio. $€_{2013}$]. ζ is the total plant availability, which has been set to 95 %.

4. Results

4.1. Simplified model results

The analysis has been performed with the meteorological data of the city of Kerak in Jordan. Fig. 1 shows the impact of both ITD and solar field specific investment cost on LEC. For this case study the CSP configuration has been kept constant (100 MW nominal power generation, solar multiple 2.0, 7.5 equivalent full load hours thermal energy storage). The analysis has been carried out for three solar field specific investment costs (300 €/m², 200 €/m² and 100 €/m²) and for an ITD range between 18 K and 40 K. The results show a clear impact of the solar field specific investment cost on LEC.

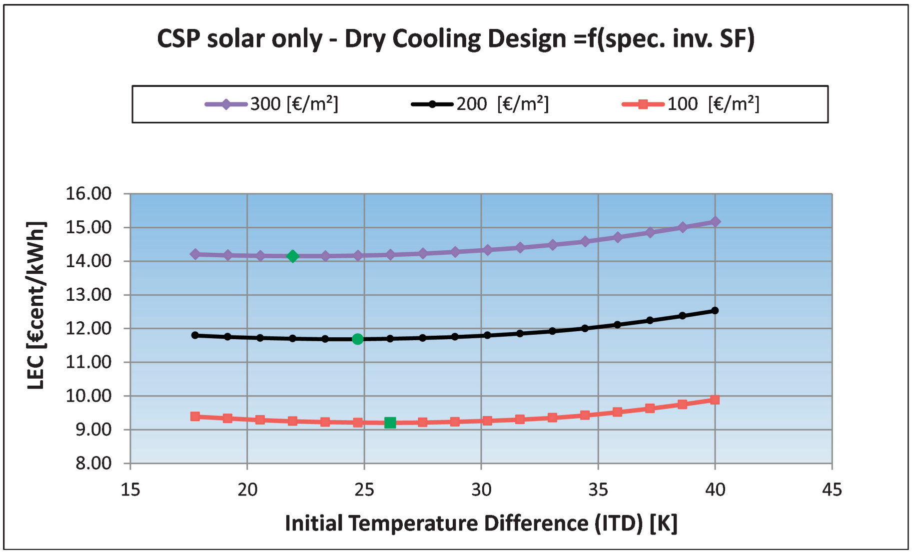

Fig. 1. LEC as function of ITD and specific solar field investment cost

It is interesting to observe that for higher solar field investment cost the optimal ITD is lower than for lower investment cost of the solar field. This can be explained with the fact that high efficiency and consequently maximal power generation is particularly important either by high CAPEX or –as it is the case in fossil fuel based power plants- high fuel cost. Conversely, if the plant CAPEX is low as well as OPEX over the complete plant lifetime, a higher investment for an efficient cooling is not justified. The second case study (Fig. 2) investigates the impact of a number ACC designs for three different CSP configurations. The first one, called SM1.3, is a configuration with an only slightly over-dimensioned solar field in comparison to the turbine heat requirements. This configuration is not equipped with TES. The other two configurations (i.e. SM2 and SM3) have a larger solar field and 7.5 and 15 equivalent full load hours TES capacity, respectively. The results show a strong dependency of the LEC on the chosen configuration. The LEC difference between the SM1.3 case and the SM3 case amounts to roughly 4.5 €c/kWh$_{el}$. Concerning the dry cooling design, it is shown that the ITD also has an effect on LEC. In addition, it is interesting to see that also the optimal ITD depends on the CSP configuration. For the SM1.3 case the optimal ITD amounts to around 25 K, which is more than the other two configurations. In this case, due to the relatively low CAPEX in comparison to the other 2 cases and to the fact that the CSP plant is in operation around 2,000 hours in the year, high investment for an even more efficient cooling do not seem to be economically advantageous. The situation changes for the other two configurations, and in particular for the SM3 case. This case is characterized by high CAPEX for solar field and TES. In this case the resulting optimal ITD is slightly above 20 K.

The optimal ITD values calculated by means of the simplified model differs from the results provided by comparable studies. In particular, according to a report by NREL and Worley Parsons [14], the optimal ITD for parabolic troughs is in the range between 14 K and 18 K, while the values founded in the current study lay between 22 K and 25 K, depending on the configuration of the CSP plant. The differences between the two studies can be explained by different assumptions regarding the investment cost of the CSP plant components, different site conditions and the difference between the design point specification Nevertheless both studies show the same trend of the LEC function which shows a minimum, even though this minimum is at a different ITD.

In addition, a further difference between the two studies is the definition of the design point specifications for the ACC. In [14], the design dry bulb temperature is defined as the 98 %-percentile of the two hottest months of the year (July and August), while in the current work the annual 80 %-percentile has been selected. Even if this choice results in efficiency losses during the hottest hours of the year, it allows to drastically reduce the investment cost of the ACC.

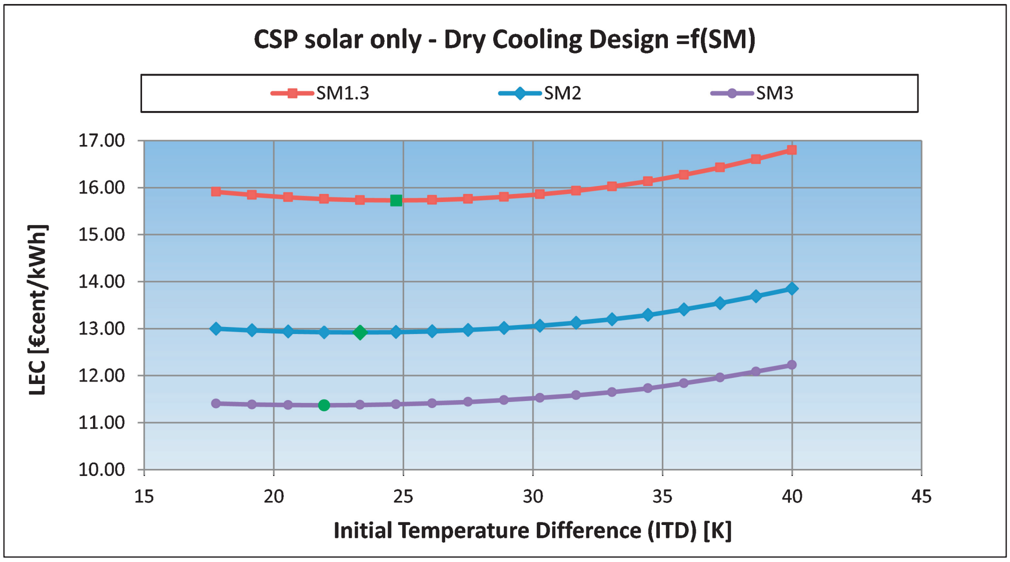

Fig. 2. LEC as function of ITD and CSP plant configuration

4.2. REMix results

The analysis has been carried out for three Jordan locations (Table 3). Two of them are inland locations with similar DNI potential and temperature distribution (maximal and average values). The third analyzed location is Aqaba, which is a coastal site characterized by lower DNI and higher average temperature in comparison with the two previous locations. The simulation has been carried out for a CSP plant with 100 MW net capacity, a SM of 1.4 and a TES capacity of 6.5 equivalent full load hours. The chosen SM and TES capacity do not necessarily represent an optimum in terms of LEC. Rather, the selection of such a solar field and storage configuration allows the REMix model for flexibility in the dispatch optimization during evening or night hours. Solar-only operation is assumed. A back-up system is considered for storage anti-freezing. The plant configuration is the same for all three cases. The design of the dry cooling unit has been performed according to the methodology presented in the previous section. In addition, three different plant operation strategies have been analyzed:

- **Standard operation:** the CSP plant continuously operates from sunrise till the TES is completely discharged or no DNI is available.
- **Optimized dispatch:** in this case the optimizing tool identifies an operation forecast schedule in order to reach the highest possible annual net power generation. The optimizations are carried out under the assumption of perfect DNI and temperature forecast.
- **Optimized dispatch with variable price:** as the assumption of a fixed feed-in price does not seem to be realistic for a large-scale market introduction of CSP into an electricity supply system, as daily and seasonal electricity demand variations would not be taken into account, a third optimized dispatch strategy was investigated, with the assumption that the feed-in tariff is directly proportional to the hourly power demand.

The main results from the simulations are summarized in Table 3. The first conclusion -which is common to all three cases- is that a LEC reduction of at least 2.0 % can be achieved by optimization of the plant dispatch in comparison to the standard operation case. The main reason for this improvement is the partial shift of plant commitment in the night hours instead of plant operation in the early evening, where the ambient temperature still is relatively high. This pattern of dispatch can be observed more often during hot summer days (Fig. 3).

Table 3. input data and results overview of different operation strategies for the three selected locations

Parameter	Unit	Kerak			Irbid			Aqaba		
Latitude	°	31.18			32.55			29.52		
Longitude	°	35.70			35.85			35.00		
DNI	kWh/m²/y	2,545			2,537			2,371		
T_{DB_AVG}	°C	17.0			17.6			24.9		
$T_{DB\_80\_\%}$	°C	25.1			24.7			32.5		
Operation Strategy	-	**Standard Operation**	**Optimized Dispatch + Fixed Price**	**Optimized Dispatch + Variable Price**	**Standard Operation**	**Optimized Dispatch + Fixed Price**	**Optimized Dispatch + Variable Price**	**Standard Operation**	**Optimized Dispatch + Fixed Price**	**Optimized Dispatch + Variable Price**
Q_{SF}	[GWh_{th}]	1180.4	1180.4	1180.4	1254.4	1254.4	1254.4	1192.4	1192.4	1192.4
$n_{start\text{-}up\ \text{-}\ PB}$	[-]	348	303	303	347	302	337	358	342	301
P_{EL_GROSS}	[GWh/y]	419.0	427.8	421.4	444.5	459.3	451.7	409.3	418.0	402.0
P_{EL_NET}	[GWh/y]	383.5	391.6	385.9	407.0	420.5	411.9	373.3	381.1	367.3
Plant Parasitics	[GWh/y]	35.4	36.2	37.6	37.4	38.9	39.8	35.9	36.9	37.4
η_{GROSS} - PB	[%]	36.5%	36.8%	36.3%	36.6%	36.9%	35.8%	35.3%	35.4%	35.2%
η_{NET} - PB	[%]	33.5%	33.8%	33.1%	33.5%	33.9%	32.3%	32.3%	32.4%	32.0%
Δ LEC	[%]	0.0%	-2.0%	3.6%	0.0%	-3.2%	-1.1%	0.0%	-2.0%	7.1%

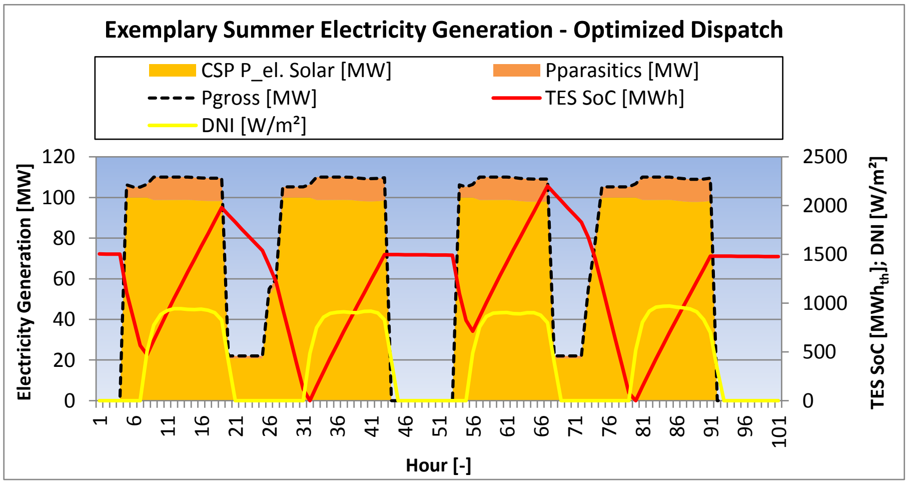

Fig. 3. optimized dispatch of a dry cooled CSP plant (Kerak - summer sample days - fixed feed-in price)

Under the assumption of a fixed feed-in price, the power generation in the evening is either reduced to the minimum possible load of 20 % or the power block is completely shut down. A further minor enhancement is given by the reduction of the number of the power block start-ups and of the consequent heat losses. It seems that no additional advantage is generated by locating the CSP plant at sites with higher temperature spread between day and night, as it is the case in Kerak. However, even if the optimized dispatch strategy would result in higher profitability for single CSP plants, the assumption of a constant feed-in price does not seem to be an advantageous market design strategy from the point of view of a power utility. This applies in particular if the power generation system is characterized by large shares of renewable energies. Therefore, a third operation strategy was analyzed, in which a demand-proportional feed-in price has been assumed. The results show that the potential for optimization by plant commitment at night is rather limited. In fact, during night hours the power demand and the price are relatively low.

5. Conclusions

As typically best DNI potentials are located in water-scarce regions, air cooled condensers will be the only viable cooling option for sustainable large-scale introduction of CSP. On the one hand, cooling efficiency in CSP plants is of key importance not only for the conversion efficiency of the power block, but also because it allows for investment savings in the solar field. On the other hand, efficient dry cooling will be cost intensive, so that a trade-off exists between cooling cost and cooling efficiency. In this paper it has been shown by means of a simplified model that solar field specific investment cost (i.e. cost of input energy) and CSP plant configuration (solar multiple, storage capacity) have an impact on the optimal design of the air cooled condenser. In particular, additional investments in efficient ACC are advantageous at high energy cost and high solar multiples. In the second part of the paper, the CSP plant commitment has been investigated for three selected locations in Jordan by the optimizing tool REMix. Three plant operation strategies have been implemented. It is shown that under the assumption of fixed feed-in tariff, the partial plant commitment in the night hours allow for a 2.0 % LEC reduction in comparison to a standard operation case. However, the consideration of a demand-proportional feed-in price, which is more realistic for an energy supply market with high renewable energy shares, shows that the potential for optimization by plant commitment at night is rather limited. In fact, during night hours the power demand and the price are relatively low. Finally, the results of the last implemented plant operation strategy shows that in average slightly higher feed-in tariffs should be introduced (in comparison to the standard case) by the regulatory authority in order to introduce a demand-driven plant commitment strategy. Even if the price of electricity by CSP plants might be a bit higher (in comparison to the standard operation), the dispatch strategy might enable to reduce the costs of the overall electricity since the CSP plants displace the most expensive plants of the merit-order system during peak load periods.

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